Diagnosing perceptual distortion present in group stereoscopic viewing

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ABSTRACT

Stereoscopic displays are an increasingly prevalent tool for experiencing virtual environments, and the inclusion of stereo has the potential to improve distance perception within the virtual environment. When multiple users simultaneously view the same stereoscopic display, only one user experiences the projectively correct view of the virtual environment, and all other users view the same stereoscopic images while standing at locations displaced from the center of projection (CoP). This study was designed to evaluate the perceptual distortions caused by displacement from the CoP when viewing virtual objects in the context of a virtual scene containing stereo depth cues. Judgments of angles were distorted after leftward and rightward displacement from the CoP. Judgments of object depth were distorted after forward and backward displacement from the CoP. However, perceptual distortions of angle and depth were smaller than predicted by a ray-intersection model based on stereo viewing geometry. Furthermore, perceptual distortions were asymmetric, leading to different patterns of distortion depending on the direction of displacement. This asymmetry also conflicts with the predictions of the ray-intersection model. The presence of monocular depth cues might account for departures from model predictions.

Keywords: Virtual environments, perception, stereoscopy, spatial judgments, vision distortion

1. INTRODUCTION

Virtual environments have become widely popular in society, and the uses for virtual reality include such diverse applications as video games, physical and psychological rehabilitation programs, training simulations, and 3D movies. One especially compelling and immersive feature of many virtual reality systems is the ability to present scenes stereoscopically. The inclusion of stereoscopic cues provides additional depth information and improves perception of egocentric (self-to-object) and exocentric (object-to-object) distances and extents. However, improper display of stereo depth cues can lead to severe perceptual distortions, and this problem is particularly pronounced in systems displayed to multiple viewers simultaneously

A common difficulty when displaying virtual environments to multiple users is providing all users with accurate stereoscopic images from their unique vantage points. In order to show the same virtual environment to multiple users, the virtual scene is usually displayed on one or more projection screen surfaces, and users wear specialized glasses which interact with the display in order to receive the left and right eye images necessary for experiencing stereopsis. When viewed by a single user, the stereoscopic images are rendered from that user's specific location, thereby providing the user with projectively correct stereo images. When head tracking is incorporated, the head-tracked user always experiences the projectively correct images, since the images are always updated from his or her current location. In this way, the user is always standing at the center of projection, or CoP, and therefore he or she should view a relatively accurate image of the virtual environment. When multiple users view the same virtual environment presented on the same screen, the image presentation becomes more complicated. Each user occupies a unique position or space in the environment, but the scene is only rendered from a single location, the CoP. Usually the CoP corresponds to the location of one user, but all other users view the same stereo images from their unique locations, which causes the additional users to perceive the virtual environment as a spatially distorted version of the intended environment. The goal of the current project was to evaluate the perceptual distortions that occur as a result of viewing the environment from locations displaced from the CoP.

Human Vision and Electronic Imaging XVII, edited by Bernice E. Rogowitz, Thrasyvoulos N. Pappas,
Huib de Ridder, Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 8291, 82910P • © 2012 SPIE-IS&T
CCC code: 0277-786X/12/$18 • doi: 10.1117/12.912184

As an example of the perceptual distortions that can occur in multi-user virtual environments, consider the case of two users viewing a virtual surgery scene. One user (the "leader") is head-tracked, and the scene is rendered from his or her perspective. The other user (the "follower") views the same stereoscopic images from his or her unique location. When both users stand in approximately the same location (e.g., side by side), the leader and follower both receive relatively accurate stereo images of the surgery environment. When the leader decides to walk around the surgery table in order to view the scene from a new perspective, the stereoscopic images displayed on the projection screen(s) change drastically, and the follower experiences dramatic changes despite having remained in the same position. Furthermore, the leader and follower now occupy different physical locations, and the images experienced by the follower are no longer appropriate for his or her location. When viewing stereo images generated from a different location (i.e., when viewing the environment from a location displaced from the CoP), the follower is likely to experience measurable perceptual distortions of spatial layout.[1]

A variety of methods have been proposed to mitigate the perceptual distortions experienced by users viewing the virtual environment from locations displaced from the CoP. Unfortunately, most of those methods lack significant user testing and/or consist of complicated implementations. Two promising techniques designed for multiple users in virtual environments are image blending and view clustering. Image blending[2] involves rendering a unique viewpoint for each head-tracked viewer using a compositing based system. This system creates a blend zone where each head-tracked user's view overlaps, and is best suited for situations in which the users' views do not overlap considerably. View clustering[2] is a technique which is more appropriate when multiple users view the same portion of a virtual environment. In this case, users' gaze-intersection points are calculated and grouped together, and the outcome is that all users experience equally distorted views.

By adopting a ray-intersection approach, the stereo viewing geometry can be used to predict the amount of perceptual distortion that will be experienced when viewing a virtual environment after displacement from the CoP.[1, 3, 4] Each point in the virtual environment corresponds to two image points on the surface of the projection screen, one of which is seen by the left eye and the other by the right eye (this is usually accomplished by wearing specialized glasses which filter out unique light wavelengths or flicker in synchrony with the display). These left- and right-eye image points are rendered from the CoP, but a viewer located elsewhere sees the same two images. By drawing two rays from the centers of the left and right eyes through the corresponding image points and out into the virtual space, the intersection point of the two rays corresponds to the predicted perceived location of the virtual point, based on the geometry of the stereoscopic cues. By considering multiple points on the same virtual object (e.g., the four corners of a virtual square), the ray-intersection method can be used to predict the perceived location and perceived dimensions of a virtual shape.

The example shown in Figure 1 demonstrates the predictions generated by the ray-intersection approach. In this scenario, two users are viewing a virtual shape formed by two connected line segments forming a 45 degree angle. The user depicted on the right is standing at the CoP, and therefore he sees accurate left and right stereo images generated from his standing location. The red circles drawn on the projection screen surfaces correspond to the left and right eye images of the two endpoints of the 45 degree red line. The user depicted on the left is displaced from the CoP, and is viewing the images that were generated from the CoP. The ray-tracing approach predicts that the virtual red line will be perceived as being displaced to the right relative to its intended location and rotated in depth relative to its intended orientation (the dashed red line indicates the intended orientation of the line when viewed from the CoP). According to the model, larger displacements should lead to larger distortions in perceived location and angle.

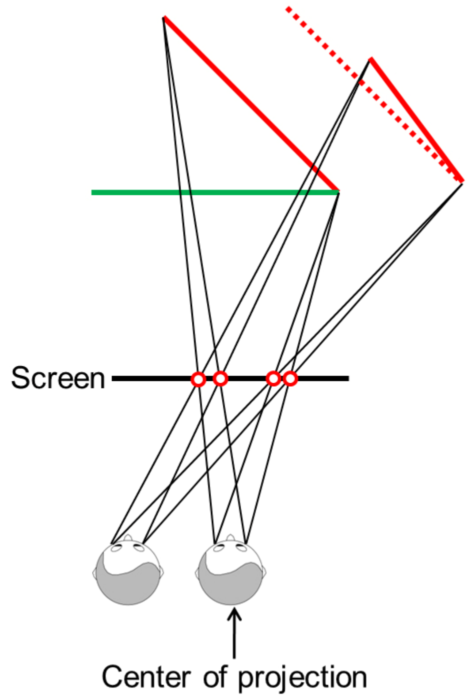

Figure 1. Two users viewing the same virtual environment, displayed in stereo on a single projection screen. The user on the right stands at the CoP, and the red circles on the screen correspond to the left and right eye images of the endpoints of the virtual red line. The user on the left is displaced from the CoP, and views the same stereo images generated from the CoP. His perception of the line, as predicted by the ray-intersection model, is displaced to the right and rotated in depth.

Recent research indicates that perceptual distortions might be fully predicted by the ray-intersection model.[1] In that study, participants adjusted a virtual hinge until it appeared to form a 90 degree angle. Adjustments made from locations displaced from the CoP were very well predicted by the ray-intersection model, suggesting that stereo viewing geometry can fully account for perceptual distortions. This contrasts with other studies using monocular displays, in which perception remains quite accurate after displacement from the CoP, especially when there is a visible border around the image.[1, 5] In sum, past work indicates that users can at least partially compensate for perceptual distortions when viewing monoscopic displays after displacement from the CoP, but not when viewing stereoscopic displays. However, the stereoscopic displays studied in past research have typically included relatively few (if any) monocular depth cues. It is therefore unknown whether stereoscopic displays will undergo significant perceptual distortion when both monocular and binocular cues are available.

The objective of the current project was to evaluate the perceptual distortions caused by displacement from the CoP when viewing virtual objects in the context of a virtual scene containing both monocular and binocular depth cues. Participants viewed virtual objects on a textured ground plane and made spatial judgments about those objects while standing at the CoP or at locations displaced from the CoP. Monocular depth information was provided by the textured ground plane, and binocular depth information was provided by the stereo images. Pilot testing revealed that forward and backward displacement from the CoP caused distortions in perceived depth of shapes (e.g., after backward displacement, a circular shape looked like an oval elongated in depth), whereas leftward and rightward displacement from the CoP caused displacement in perceived angles (e.g., after leftward displacement, a right angle looked like an obtuse angle; see Figure 1). In order to better understand these distortions, participants made depth judgments and angle judgments while viewing virtual rectangles and virtual angles, respectively.

Past work on virtual environments indicates that distance is typically underestimated, even when the environment is viewed from the CoP.[6, 7, 8, 9, 10, 11, 12, 13,14,15] In real-world environments, distances are typically perceived quite accurately, especially under full-cue viewing conditions.[16] The exact cause of distance compression in virtual environments is unclear, and is an ongoing topic of research.

2. METHODOLOGY

2.1 Method

Twenty students at Iowa State University participated in the study. Participants received research credit or $10 for participating in the study. All participants gave informed consent to a protocol approved by the Iowa State University Institutional Review Board.

2.2 Stimuli and design

The experiment was conducted within the C6 (Figure 2), a virtual reality system with a six-sided configuration of projection screens measuring 10 x 10 x 10 ft. The virtual environment was created using OpenSceneGraph and VR Juggler[17], a commonly used API for clustered graphics applications. Each screen of the C6 was back-projected with 4,000 pixel stereo resolution per screen. The retractable rear screen was not used, due to its location directly behind the participant (i.e., outside of the participant's field of view). Shutter-glasses synchronized with the projectors were used so participants could receive stereoscopic depth cues.

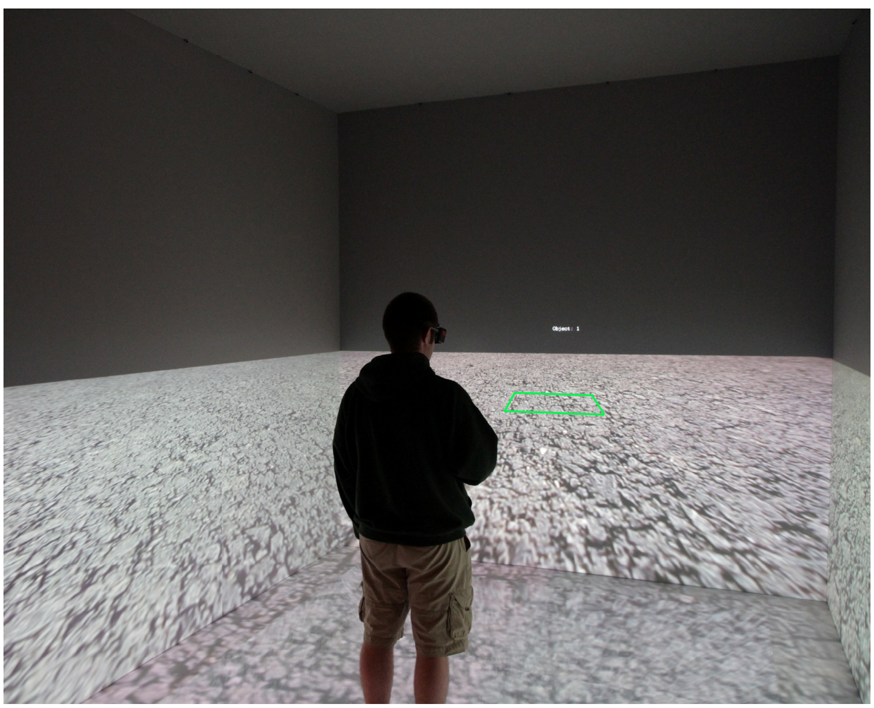

Figure 2. A participant stands in the C6 viewing the virtual environment used in the experiment. The virtual green rectangle in front of the participant is one of the stimuli used to evaluate perceived depth and perceived width.

The stimuli used in the virtual environment consisted of angles and rectangles. Angle stimuli were formed by a green line, perpendicular to the participant's view, and a red line rotated in depth (see Figure 1). The angle vertex was always on the right side of the shape. The green and red lines were each 3 feet in length, and the angle formed by the two lines ranged from 15 to 165 degrees in 15 degree increments, resulting in 11 unique angles. Angles were placed either 10 or 16 feet in front of participants, resulting in 22 total combinations of angle and distance. Rectangle stimuli were formed by four green lines in the outline of a rectangle (see Figure 2 for an example). The depth and width of the rectangle could be 2, 4, or 6 feet, resulting in 9 rectangles of varying depth and width. Rectangles were placed either 10 or 16 feet in front of participants, resulting in 18 total combinations of depth, width, and distance. Angles and rectangles appeared on an infinite ground plane covered with an irregular texture. The height of the ground plane was identical to the floor height in the C6.

Participants made angle judgments while standing at the CoP or after displacement by 3.5 feet leftward or rightward from the CoP (see Figure 3, left panel). Participants made depth and width judgments while standing at the CoP or after displacement by 2.5 feet forward or backward from the CoP (see Figure 3, right panel). Forward and backward displacements were smaller than leftward and rightward displacements due to visual discomfort experienced when viewing the front projection screen from a very close distance.

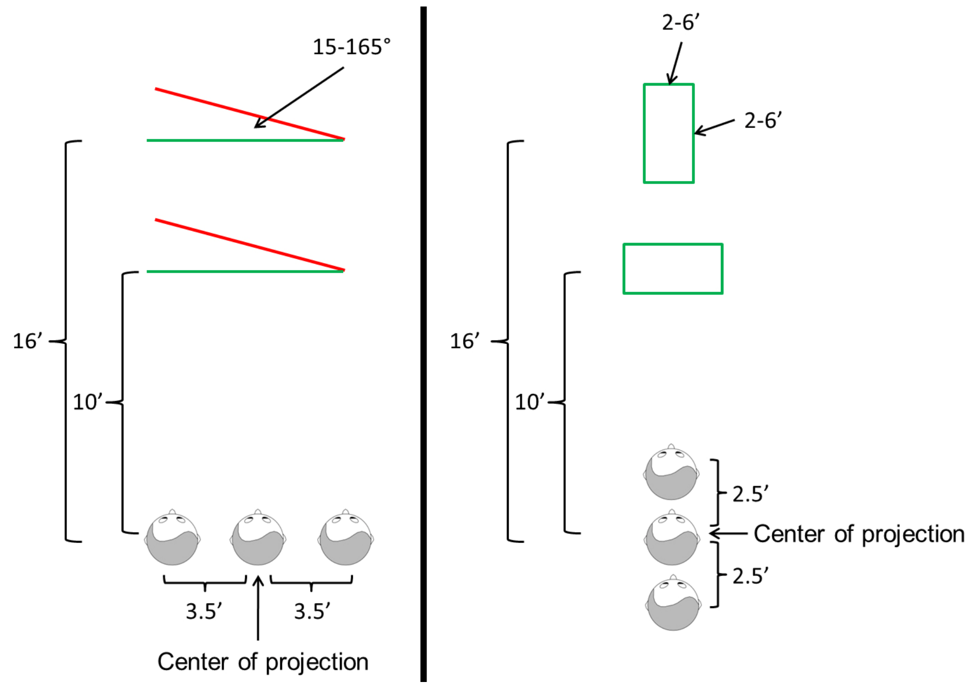

Figure 3. Stimuli used in the experiment. The left panel shows the viewing locations and the virtual shapes used for angle judgments. The right panel shows the viewing positions and virtual shapes used for depth and width judgments.

Angle judgments and depth and width judgments were blocked, and block order was counterbalanced. Within each judgment type block, viewing position was also blocked and order was counterbalanced. For each viewing position, angle stimuli and rectangle stimuli were presented in a random sequence.

2.3 Procedure

Upon providing informed consent, participants completed a demographic form which asked questions about age, previous experiences with virtual reality, and presence of vision problems that could influence perception of experimental stimuli. Participants were then given a brief training session in which the experimenter showed them angles and rectangles formed by lines on the laboratory floor. Training was done in the real world, and therefore was not expected to bias perceptions of objects in the virtual environment. The purpose of the training was to familiarize participants with making judgments of angle, width, and depth, and to make sure the participant understood how to report those judgments in the relevant units of measurement. For each type of judgment (angle, width, and depth), participants were first shown a sample object and were told the correct answer. After this demonstration, participants were shown a new sample object and were asked to report what they believed to be the correct answer, and participants were given feedback. When making width and depth judgments, participants were allowed to use the unit of measurement they felt most comfortable with. Most participants chose to use feet, and responses that were given in alternative units were converted to feet prior to analysis.

After training, the participant donned shutter glasses and was directed into the C6. The participant was placed at the center viewing position, facing the front screen, and the head tracking system was locked at that position. Locking the head tracking mechanism at the center position ensured that the CoP did not change when the participant was moved to a new location.

Participants were instructed on which type of judgment they would be making first and where they should stand. Responses to angle judgments and depth and width judgments were given verbally, and the experimenter recorded the responses.

After completing all judgments in all conditions, participants were asked a series of questions designed to determine whether they were aware of the perceptual distortion when viewing the environment after displacement from the CoP. They were first asked if they noticed anything strange about the environment. Participants were then asked more specifically if they noticed anything unusual about the shapes and the angles when viewed from different positions. Participants responded verbally and all responses were recorded by the experimenter.

3. RESULTS

3.1 Angle judgments

Angle judgments made from each viewing position and for each object distance (10 feet or 16 feet) are shown in Figure 4. Angle judgments were analyzed in a repeated measures ANOVA with terms for object angle (15-165 degrees), object distance (10 feet or 16 feet), and participant viewing position (center, left, or right). Judgments of the smallest and largest angles were unaffected by standing position, but judgments of intermediate angles were significantly affected by standing position. This pattern of judgments led to a significant interaction between stimulus angle and viewing position, $F(20,380)=14.86$, $p<.001$. Intermediate angles, especially those between 45 and 135 degrees, were judged as larger than their actual size when viewed from the left position and smaller than their actual size when viewed from the right position. Judgments were relatively accurate from the center viewing position. This pattern of over- and underestimation from the left and right viewing positions, respectively, was unaffected by the distance of the angle from the participant, $F(20,380)=0.84$, ns.

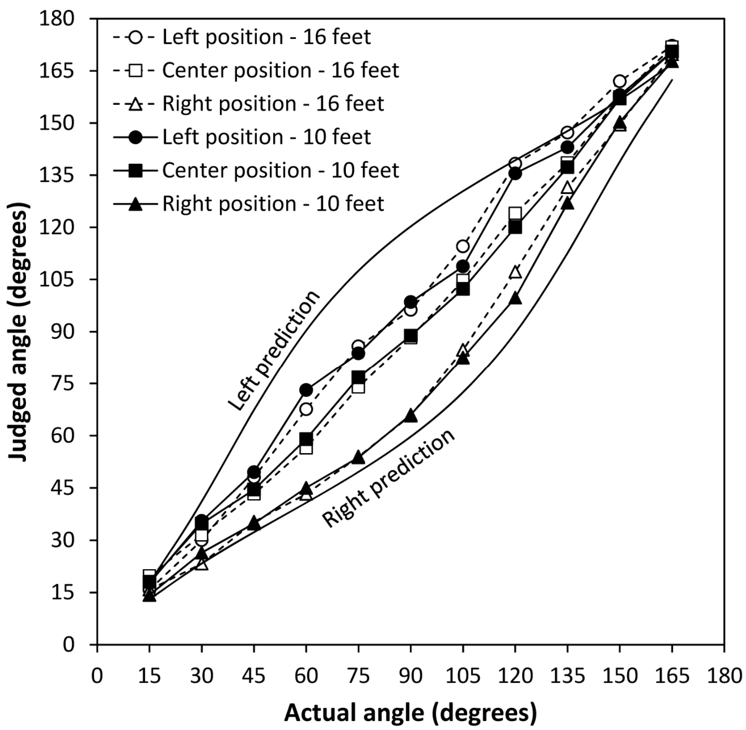

Figure 4. Angle judgments as a function of actual angle, viewing location, and object distance. The predictions of the ray-intersection model after leftward and rightward displacement are also depicted

Predictions of the ray-intersection model (based on the stereo viewing geometry) are also shown in Figure 4. Despite the significant over- and underestimation of angles when standing in the left and right viewing positions, errors were significantly smaller than predicted by the ray-intersection model. In order to statistically evaluate judgments relative to the model, angle judgment errors were calculated relative to the model predictions. Because distance to the object did not affect angle judgments, the two distances were combined for this calculation. These data are shown in Figure 5, where negative values are errors that were smaller than the model predictions (i.e., judgments that were closer to the actual angle than predicted) and positive errors are errors that were larger than the model predictions. As seen from Figure 5, model-relative errors were generally negative, meaning that judgments were smaller than predicted by the model.

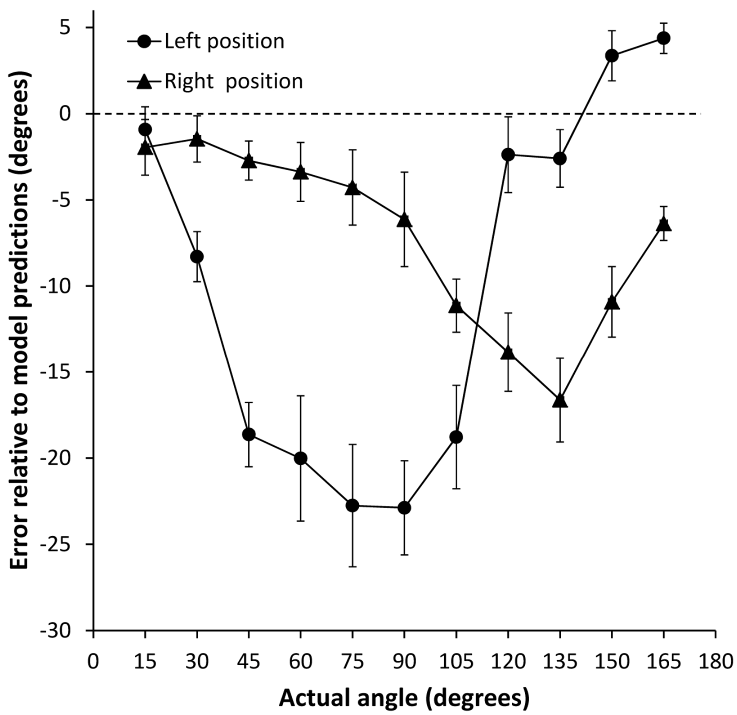

Figure 5. Errors in angle judgments relative to the predictions of the ray-intersection model. Positive errors are errors that were larger (i.e., farther from the correct angle) than predicted by the model, and negative errors are errors that were smaller (i.e., closer to the correct angle) than predicted by the model.

Judgment errors relative to model predictions were evaluated in a repeated measures ANOVA with terms for actual angle (15-165 degrees) and viewing position (left or right). Judgments were closest to model predictions (i.e., model-relative errors in Figure 5 were closest to zero) for the smallest and largest angles, $F(10,190)=17.84$, $p<.001$. However, the pattern was different for the two viewing positions, $F(10,190)=22.84$, $p<.001$. When standing in the left viewing position, judgments of larger angles were more likely to be biased toward the model predictions than were judgments of smaller angles. When standing in the right viewing position, judgments of smaller angles were more likely to be biased toward the model predictions than were judgments of larger angles. This asymmetry is not predicted by the ray-intersection model, and it might be due to the fact that the angles always opened toward the left (i.e., the vertex was on the right side of the angle).

3.2 Depth and width judgments

Depth judgments (shown in Figure 6) were analyzed in a repeated measures ANOVA with terms for actual object depth (2, 4 or 6 feet), viewing position (front, center, or back position), and object distance (10 or 16 feet). All main effects and interactions were significant at p<.01. Regardless of viewing position or object distance, larger depth judgments accompanied increased object depth, $F(2,38)=58.72$, $p<.001$. Furthermore, viewing position also had a significant effect on judged depth, $F(2,38)=26.27$, $p<.001$, such that depth judgments were larger when standing at the center or back viewing positions compared to the front viewing position. Object distance also significantly affected depth judgments, such that nearer objects were judged to have a greater depth than farther objects, $F(1,19)=26.30$, $p<.001$.

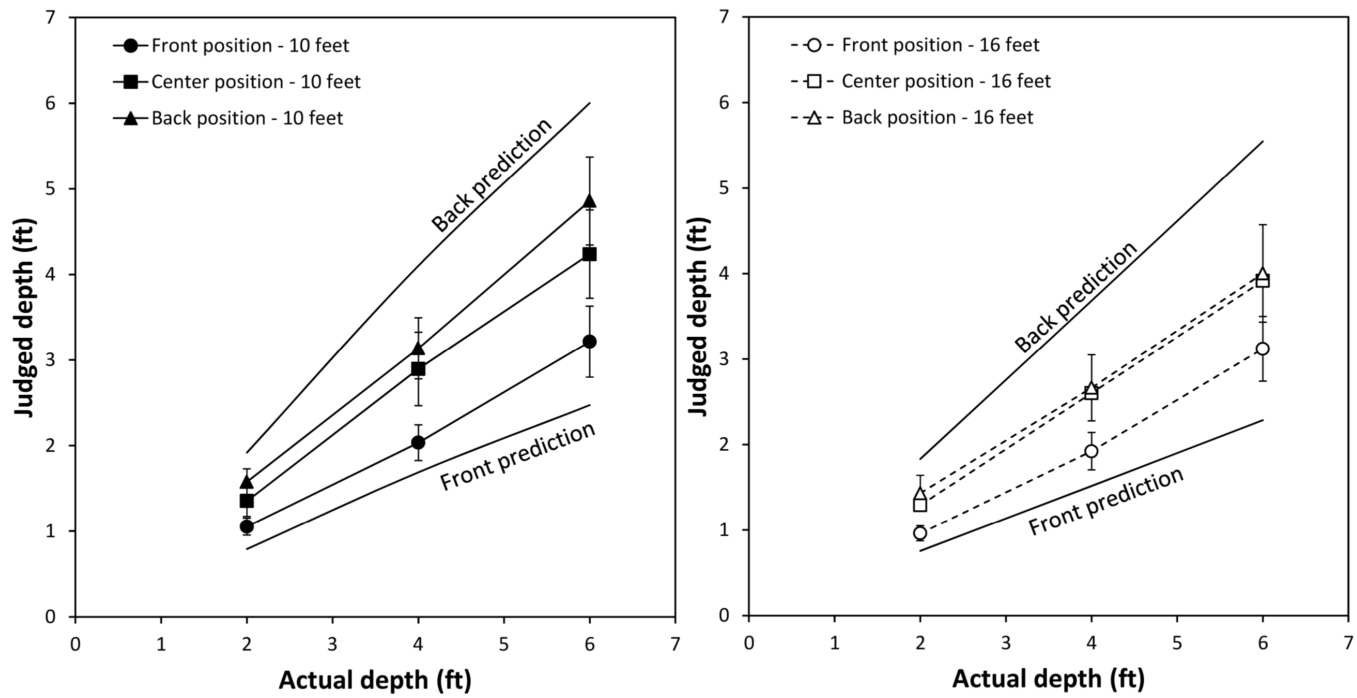

Figure 6. Depth judgments shown as a function of actual object depth, participant viewing location, and distance of the object from the participant (Left panel: 10 foot distance; Right panel: 16 foot distance. The predictions of the ray-intersection model after forward and backward displacement are also depicted.

Depth judgments made from the center viewing position were significantly foreshortened, averaging 70.2% of actual object depth for objects at 10 feet from the viewer, $t(19)=3.17$, $p=.005$, and 64.9% of actual object depth for objects at 16 feet from the viewer, $t(19)=3.59$, $p=0.002$. This is consistent with previous reports of perceived depth compression in virtual environments.[16] Based on the compressed depth judgments when participants stood at the center viewing position (i.e., at the CoP), depth judgment predictions generated by the ray-intersection model were scaled accordingly. Specifically, model-predicted depth was scaled by 70.2% for objects at 10 feet from the participant and by 64.9% for objects at 16 feet from the participant (scaled predictions for forward and backward displacements are labeled as "front prediction" and "back prediction" in Figure 6).

For objects 10 feet from the participant, depth judgments made from the front viewing position were 21.0% smaller than judgments made from the center viewing position. This compression was significantly less than the scaled predictions of the model, in which depth judgments made from the front viewing position were predicted to be 41.7% smaller than judgments made from the center viewing position, $t(19)=7.47$, $p<.001$. Depth judgments made from the back viewing position were 18.2% larger than judgments made from the center viewing position. This expansion was significantly less than the scaled predictions of the model, in which depth judgments in the back viewing position were predicted to be 41.7% larger than judgments made from the center viewing position, $t(19)=8.27$, $p<.001$.

For objects 16 feet from the participant, depth judgments made from the front viewing position were 16.6% smaller than judgments made from the center viewing position. This compression was significantly less than the scaled predictions of the model, in which depth judgments made from the front viewing position were predicted to be 41.7% smaller than judgments made from the center viewing position, t(19)=6.89, p<.001. Depth judgments made from the back viewing position were 14.5% larger than judgments made from the center viewing position. This expansion was significantly less than the scaled predictions of the model, in which depth judgments in the back viewing position were predicted to be 41.7% larger than judgments made from the center viewing position, t(19)=5.05, p<.001.

Distortion of perceived depth relative to judgments made from the center viewing position was larger after forward displacement compared to backward displacement. This indicates an asymmetric bias toward larger distortion after forward displacement compared to backward displacement.

Width judgments (shown in Figure 7) were analyzed in a repeated measures ANOVA with terms for actual object width (2, 4 or 6 feet), viewing position (front, center, or back position), and object distance (10 or 16 feet). Regardless of viewing position or object distance, larger width judgments accompanied increased object width, F(2,38)=69.49, p<.001. Furthermore, viewing position also had a significant effect on judged width, F(2,38)=3.86, p=.03, such that width judgments were larger when standing at the center or back viewing positions compared to the front viewing position. Judgments made while standing at the center and back viewing positions did not differ. The difference between width judgments made from the center and back viewing positions compared to the front position increased with increasing object width, leading to a significant interaction between viewing position and object width, F(4,76)=2.98, p=.024. The ray-intersection model predicts that perceived width should be unaffected by changes in viewing location.

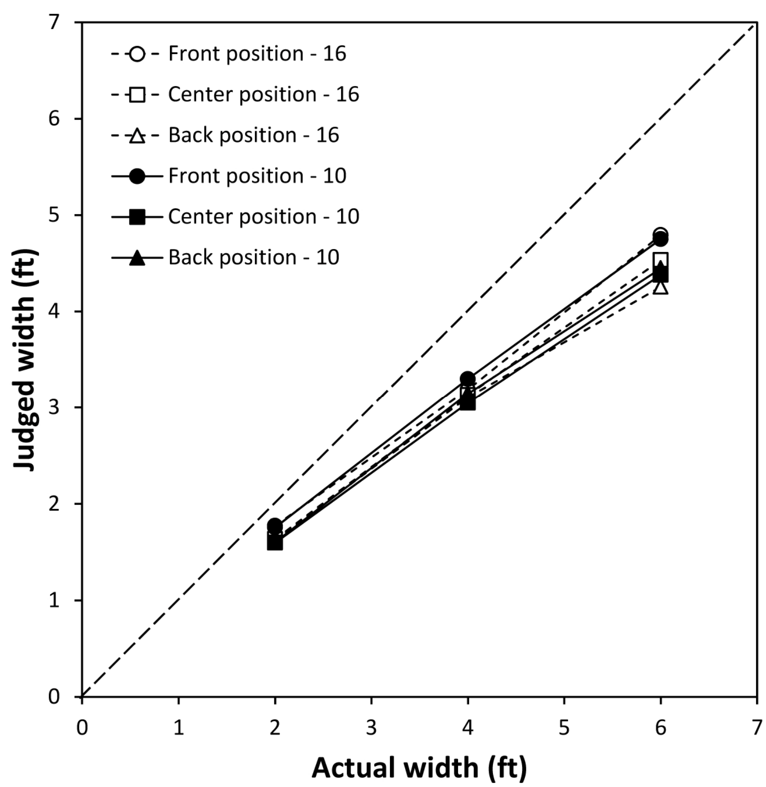

Figure 7. Width judgments shown as a function of actual object width, participant viewing location, and distance of the object from the participant.

4. CONCLUSION AND FUTURE WORK

The primary purpose of this study was to evaluate the perceptual distortions that occur when viewing stereoscopic virtual environments after displacement from the CoP. To that end, lateral displacement of the viewing position relative to the CoP led to large errors in judgments of angles formed by two line segments on the ground plane, and fore-aft displacements from the CoP led to large errors in judgments of the depth of rectangular shapes on the ground plane. In both cases, perceived distortions were in the direction predicted by the ray-intersection model based on stereo viewing geometry. Angles were under/over-perceived after rightward/leftward displacement, and depths were under/over-perceived after forward/backward displacement. However, the magnitude of these distortions was consistently less than predicted by the ray-intersection models.

In contrast to the current findings, previous work on perceptual distortion after displacement from the CoP found that distortion could be fully accounted for by the stereo viewing geometry.[1] One possible explanation for the discrepant findings is the presence of monocular depth cues in the current study. Participants in this study judged shapes appearing on the ground, which provided monocular depth cues in addition to the stereo depth cues. The primary monocular depth cues present in this study were defined by the texture gradient on the ground plane[18] and the angle of declination from the eyes to the object on the ground.[19] In the study by Banks and colleagues[1], participants viewed a hinge at eye level, and depth was defined primarily by stereo cues and a weak texture on the hinged surfaces. The availability of monocular depth cues in the current study may have allowed participants to partially correct for the perceptual distortion caused by the incorrect stereo cues. This conjecture is supported by work showing that monocular displays are relatively immune to distortions caused by displacement from the CoP.[5]

Judgments of perceived angle and judgments of perceived depth were asymmetric. For angle judgments, leftward displacement from the CoP led to greater distortion of obtuse angles, whereas rightward displacement from the CoP led to greater distortion of acute angles. The exact cause of this asymmetry is unclear and is not predicted by the ray-intersection model. However, the asymmetry may be related to the direction of the angle vertex, which was always on the right side. Switching the angle vertex to the left side might result in a reversal of this pattern, but further work is needed to evaluate this.

For depth judgments, forward displacement from the CoP led to greater distortion of perceived object depth than did backward displacement. This finding is not predicted by the ray-intersection model, and future work is needed to evaluate the cause.

When displaying a virtual environment to multiple users, one user (the leader) is typically head-tracked and receives the correct stereoscopic images generated from his or her current position. In this way, the leader is always standing at the CoP and should see a relatively undistorted view of the virtual environment. All other users, the followers, view the same stereoscopic images intended for the leader. However, the followers stand in locations displaced from the CoP, and therefore are likely to see a distorted version of the virtual environment. The results of this project identify some of the properties of the distorted environment seen by the followers, and the types of perceptual distortions that are likely to occur after lateral and fore/aft displacements. Further work is needed to better understand the relationship between these perceptual distortions and the predictions generated by the ray-intersection model. Another important direction for future research is to understand how these perceptual distortions affect collaboration between the leader and followers and between multiple followers.

ACKNOWLEDGEMENTS

This work was supported by a grant from the United States Army RDECOM – STTC.

REFERENCES

[1] Banks, M., Held, R., and Girshick, A., "Perception of 3-D Layout in Stereo Displays," Information Display 25 (1), 12-16 (2009).

[2] Marbach, J., "Image Blending and View Clustering for Multi-Viewer Immersive Projection Environments," Proc. of IEEE Virtual Reality Conference (2009).

[3] Held, R.T., and Banks, M.S., "Misperceptions in Stereoscopic Displays: A Vision Science Perspective," Proc. of the 5th Symp. on Applied Perception in Graphics and Visualization (APGV '08), ACM (2008).

[4] Woods, A., Docherty, T., and Koch, R., "Image Distortions in Stereoscopic Video Systems," SPIE Proc. Stereoscopic Displays and Applications IV, 1915, 36-48 (1993).

[5] Vishwanath, D., Girshick, A., and Banks, M., "Why Pictures Look Right When Viewed from the Wrong Place," Nature Neuroscience, 8 (10), 1401-1410 (2005).

[6] Bodenheimer, B., Meng, J.H., Narasimham, W., Rump, G.B., McNamara, T.P., Carr, T.H., and Rieser, J.J., "Distance Estimation in Virtual and Real Environments Using Bisection," Proc. of the 4th Symp. on Applied Perception in Graphics and Visualization (2007).

[7] J.M. Knapp and J.M. Loomis, "Limited Field of View of Head-Mounted Displays Is Not the Cause of Distance Underestimation in Virtual Environments," Presence: Teleoperators and Virtual Environments 13 (5), 572-577 (2004).

[8] Kuhl, S.A., Thompson, W.B., and Creem-Regehr, S.H., "HMD Calibration and its Effects on Distance Judgments," ACM Trans. Appl. Percept., 6 (3), art. 19, 1-20 (2009).

[9] Messing, R., and Durgin, F.H., "Distance Perception and the Visual Horizon in Head-Mounted Displays," ACM Trans. Appl. Percept., 2 (3), 234-250 (2005).

[10] Plumert, J.M., Kearney, J.K., and Cremer, J.F., "Children's Perception of Gap Affordances: Bicycling Across Traffic-Filled Intersections in an Immersive Virtual Environment," Child Development, 75 (4) 1243-1253 (2004).

[11] Steinicke, F. , Bruder, G., Ries, B., Hinrichs, K.H., Lappe, M., and Interrante, V., "Transitional Environments Enhance Distance Perception in Immersive Virtual Reality Systems," Proc. of Symp. on Applied Perception in Graphics and Visualization (2009).

[12] Thompson, W.B. , Willemsen, P., Gooch, A.A. , Creem-Regehr, S.H., Loomis, J.M. , and Beall, A.C., "Does the Quality of the Computer Graphics Matter when Judging Distances in Visually Immersive Environments?," Presence: Teleoperators and Virtual Environments, 13 (5), 560-571 (2004).

[13] Gooch, A.A., and Willemsen, P., "Evaluating Space Perception in NPR Immersive Environments," Proc. of the 2nd Int. Symp. on Non-Photorealistic Animation and Rendering (NPAR '02), ACM (2002).

[14] Witmer, B.G., and Sadowski, W.J., "Nonvisually Guided Locomotion to a Previously Viewed Target in Real and Virtual Environments," Human Factors: The Journal of the Human Factors and Ergonomics Society, 50 (3), 478-488 (1998).

[15] Ziemer, C., Plumert, J., Cremer, J., and Kearney, J.,"Making Distance Judgments in Real and Virtual Environments: Does Order Make a Difference?," Proc. of the 3rd Symp. on Applied Perception in Graphics and Visualization (APGV '06), ACM (2006).

[16] Loomis, J. , and Knapp, J., "Visual Perception of Egocentric Distance in Real and Virtual Environments," Virtual and Adaptive Environments: Applications, Implications, and Human Performance Issues (2003).

[17] Cruz-Neira, C., Bierbaum, A., Hartling, P., Just, C., and Meinert, K.,"VR Juggler - An Open Source platform for virtual reality applications" 40th AIAA Aerospace Sciences Meeting & Exhibit (2002).

[18] Wu, B., Ooi, T.L., and He, Z.J., "Perceiving distance accurately by a directional process of integrating ground information," Nature, 428, 73-77 (2004).

[19] Ooi, T.L., Wu, B., and He, Z.J., "Distance determined by the angular declination below the horizon," Nature, 414, 197-200 (2001).